

QUALITY OF WATER RECOVERED FROM A MUNICIPAL EFFLUENT INJECTION
WELL IN THE FLORIDAN AQUIFER SYSTEM, POMPAÑO BEACH, FLORIDA

By Donald J. McKenzie and G. A. Irwin

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ABSTRACT

Approximately 69 million gallons of backflow from an injection well used for the disposal of secondary treated municipal effluent in the Floridan aquifer system near Pompano Beach, Florida, was periodically sampled for inorganic and organic quality from March 1975 through March 1977. Analyses of the backflowed effluent showed a concomitant increase in dissolved solids and a change in ionic composition as a function of cumulative volume of backflow. Both the increase in dissolved solids and the change in major ionic composition were directly related to the mixing of an estimated 6 to 7 percent of the moderately saline water in the Floridan aquifer system with the injected effluent. Although an estimated 3.5 billion gallons of effluent with an estimated chloride concentration of 84 milligrams per liter was injected into the aquifer system during the 16-year operation of the Collier Manor treatment plant, only 65 to 70 million gallons (about 2 percent of the total effluent) was recovered before the chloride concentration approached 250 milligrams per liter.

Unlike the more conservative major inorganic constituents, the levels of nitrogen, phosphorus, and hydrogen sulfide decreased with cumulative backflow. The reduction in concentrations of these nonconservative variables in the final backflow samples exceeded that which was likely caused by a 6 to 7 percent mixing of the water in the Floridan aquifer system with injected effluent. The decreases of many nonconservative variables, therefore, were probably the result of both mixing and other processes such as ion exchange, sorption, bacterial activity, and chemical precipitation.

Overall, the recovered effluent was of poor quality and was not suitable for most uses under existing State regulations. Additionally, the inorganic quality of the injected effluent was further degraded as a result of mixing with the moderately saline native water.

INTRODUCTION

The practice of subsurface disposal of liquid wastes by injection methods has been used in the State of Florida since the early 1900's. One of the most notable of the vintage disposal techniques is used in the Orlando area of central Florida where stormwater runoff has been discharged by means of drainage (gravity) injection wells into the Floridan aquifer system since the turn of the century. Disposal of stormwater runoff through drainage injection wells is also commonplace in other parts of Florida. Although precise records are lacking, there may be several thousand drainage injection wells that are actively used for stormwater disposal in peninsular Florida (Vecchioli, 1981).

At a limited number of sites in Florida, treated domestic sewage, oil field brines, and organic and inorganic liquid byproducts discharged from industrial and manufacturing activities are being injected into the subsurface. These disposal facilities are pressure (pumped) injection systems rather than drainage injection systems. In 1979, there were 10 disposal systems using pressure injection in Florida--5 for the disposal of industrial liquid waste and 5 for municipal wastewater. The average injection rate for the industrial systems was about 5.5 Mgal/d and 38 Mgal/d for the municipal waste systems (Vecchioli, 1981). A detailed description of most of the active waste injection systems in Florida, along with an extensive bibliography of research activities on subsurface injection of liquid waste, can be found in Vecchioli and others, 1979, and Kimrey and Fayard, 1982.

The use of subsurface injection as a method of liquid waste disposal will likely increase in many areas of Florida. Growth in subsurface disposal is anticipated because the hydrogeology in many parts of Florida is conducive to liquid waste injection and because recent water pollution control legislation discourages surface disposal. Injection of treated municipal effluent in southeast Florida is expected to have the largest growth (Vecchioli, 1981).

In anticipation of future data requirements regarding injection of treated municipal effluent, the U.S. Geological Survey, in cooperation with the Florida Department of Environmental Regulation and the Broward County Utilities Department, conducted a sampling reconnaissance of secondary treated effluent recovered from a moderately saline zone of the Floridan aquifer system. The sampling was conducted at the Broward County Utilities Department system C-2 wastewater treatment plant (Collier Manor) in Pompano Beach, Fla., where about 3.5 billion gallons of municipal effluent had been pressure injected into the Floridan aquifer system from 1959 to 1975.

The primary purpose of this investigation and report was to measure and describe the variation in levels of selected physical and chemical variables (parameters) during a 69 million gallon backflow of the injected effluent. This data collection was designed to provide background and furnish documentation of the general efficacy of recovery of injected treated municipal effluent.

The scope of this reconnaissance included the collection of 40 samples of backflowed effluent for selected analyses during the 69 million gallon backflow period. The sampling periods were March to August 1975 and April 1976 to March 1977. The collection of detailed geophysical and geohydrological data were not within the scope of this study as it was not designed as an in-depth evaluation of the flow system or the geochemical processes in the injection zone of the aquifer system.

DESCRIPTION OF THE COLLIER MANOR WASTEWATER TREATMENT PLANT

Background

The Broward County Utilities Department system C-2 (Collier Manor) wastewater treatment plant in Pompano Beach began operation in 1959 as a privately owned utility (fig. 1). The plant treated and injected effluent from a service area of single family residences, a shopping mall, and a small industrial park during its 16-year operation. The Broward County Utilities

Department assumed operation of the Collier Manor wastewater treatment plant in 1969 and continued its operation until 1975. Collier Manor was abandoned in January 1975 when its function was transferred by the county to the new Broward County north regional water and wastewater treatment plant.

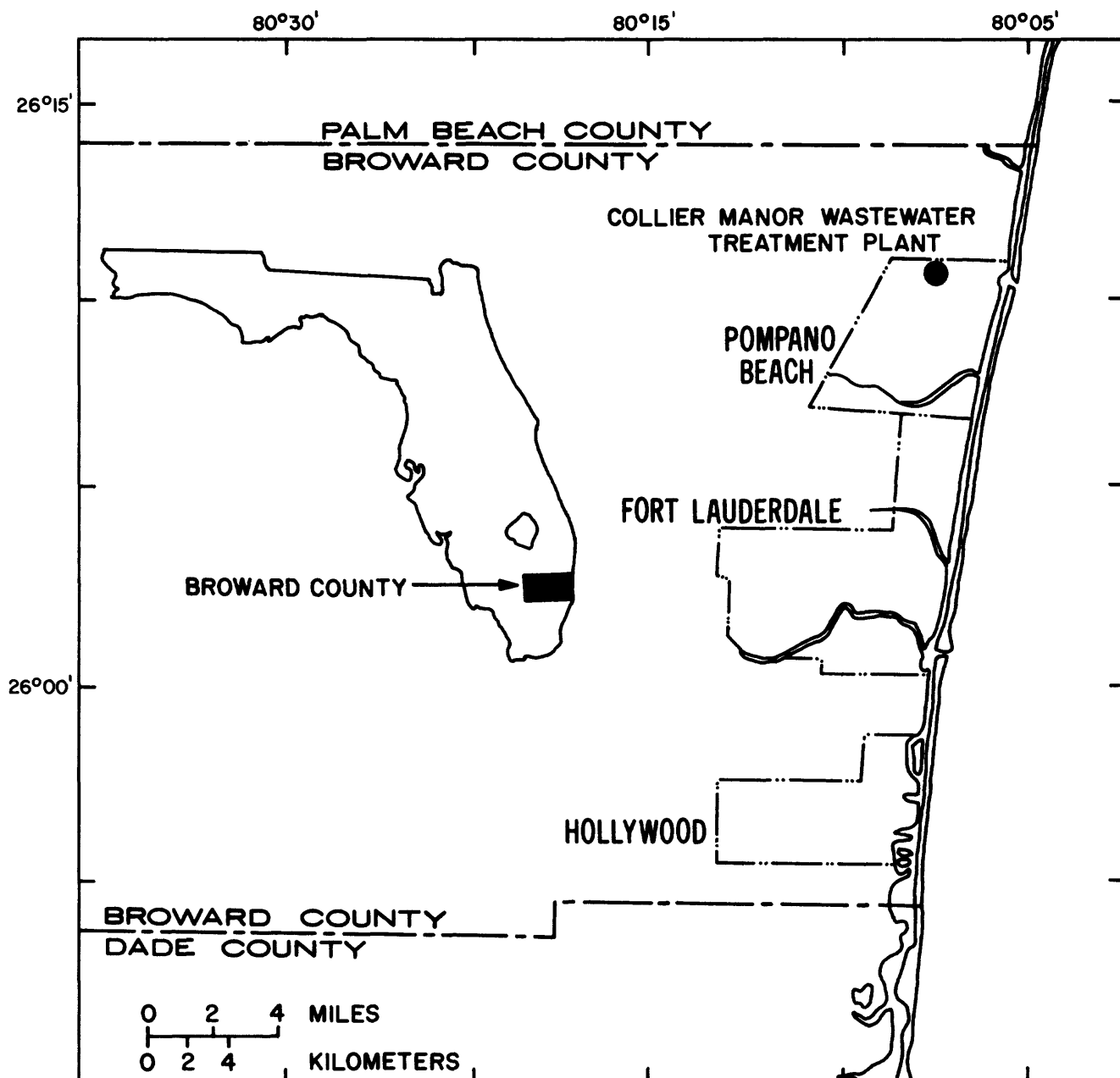


Figure 1.--Location of Collier Manor wastewater treatment plant, Pompano Beach, Florida.

The average injection rate of the secondary treated effluent for the approximate 16-year operation is estimated at about 0.6 Mgal/d; however, injection rates at the plant did increase slightly over the years. Grantham and Sherwood (1968) reported an average injection rate of about 0.45 Mgal/d for Collier Manor during the early 1960's; and Sherwood and others (1973) reported an average injection rate of 0.50 Mgal/d during the middle 1960's. From the late 1960's until the time the plant was abandoned in 1975, the average injection rate was estimated to be about 0.6 to 0.7 Mgal/d. The total volume of effluent that was injected into the Floridan aquifer system during the plant's operation is estimated at about 3.5 billion gallons. This estimate is based on approximately 16 years of operation with an average injection rate of 0.6 Mgal/d.

Wastewater Treatment Plant and Injection System

The Collier Manor wastewater treatment plant was a high-rate trickling filter, anaerobic system which consisted of primary sedimentation, high-rate filtration, secondary sedimentation, and chlorination prior to injection.

The injection system consisted of two wells located about 350 feet apart (fig. 2). Injection well 1 was constructed in 1959 and was operated until 1975 and injection well 2 was constructed in 1970 and was operated until 1975. Injection well 1 was drilled to a depth of 1,150 feet and was completed with 10-inch casing to a depth of 1,004 feet. Injection well 2 was drilled to a depth of 1,250 feet and was completed with 12-inch casing to a depth of 995 feet.

Injection pressures at the wellheads during operation averaged 85 to 95 lbf/in². The average shut-in pressure of the injection wells, at least during the latter period of operation, was about 25 lbf/in². Clogging of the injection wells was commonplace; thus, it was routine plant procedure to backflush the injection wells about 1 hour per week, and when wellhead pressures increased to above 100 lbf/in² additional backflushing was performed. On three occasions, the injection wells (well 1 once, well 2 twice) were acidized with about 1,000 gallons of industrial grade hydrochloric acid to alleviate clogging.

METHODS AND PROCEDURES

Backflow and Sampling Procedures

Collier Manor injection well 2 was used for the backflow sampling (fig. 2). To prevent possible disruption of the treatment process at the regional treatment plant which was receiving the backflow from the Collier Manor test site, the backflow test was discontinued in March 1977 at a cumulative volume of about 69.2 Mgal when the concentration of chloride reached about 250 mg/L.

Well 2 was initially backflowed under artesian pressure at an average rate of about 4 gal/min (gallons per minute) from late March until August 1975 (fig. 3). The low backflow was maintained initially because of the uncertainty as to how rapidly the chloride concentration would reach 250 mg/L. The chloride concentration was about 77 mg/L and the cumulative volume of backflow was about 0.76 Mgal when the initial backflow of 4 gal/min was discontinued in

August 1975 for the purpose of increasing the backflow capacity. Because of operational difficulties in obtaining equipment to increase flow rate and delays in equipment installation, however, the modification of well 2 was not completed until March 1976. Consequently, the final backflow sampled at the higher artesian flow of 132 gal/min was resumed April 1976 and continued through late March 1977.

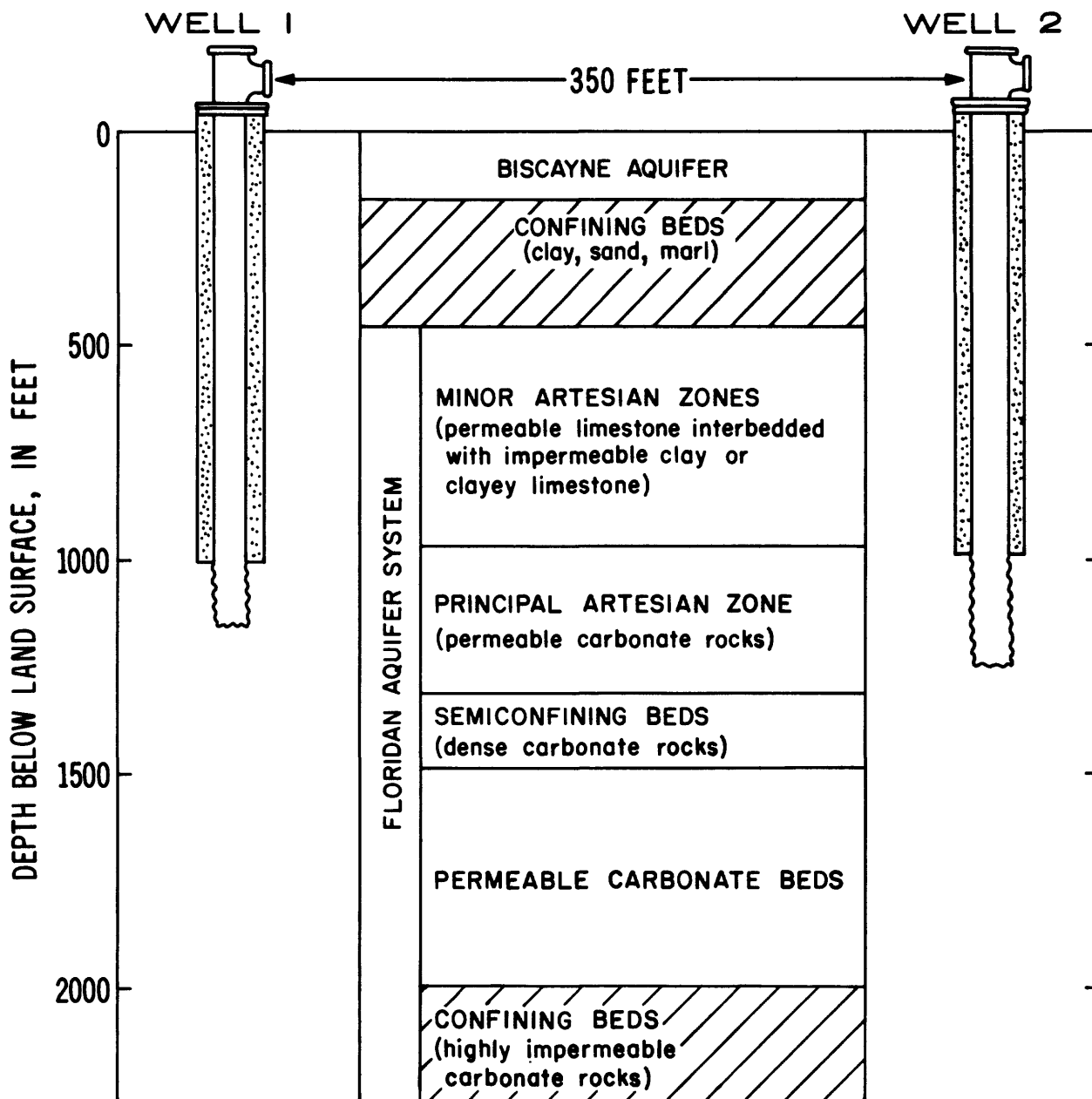


Figure 2.--Generalized hydrogeologic section and sketch of the injection wells at the Collier Manor wastewater treatment plant.



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March 1977.

Water samples were collected periodically during both backflow periods. Thirteen samples for selected parameters were collected during the March to August 1975 backflow period and 27 samples were collected during the April 1976 to March 1977 backflow. The backflow was not discontinued until March 1977 at a cumulative volume of 69.2 Mgal, but the final sample for most variables was collected on February 12, 1977, at a cumulative volume of 66.1 Mgal.

Analytical Methods and Field Procedures

Water samples were analyzed using the methods described in Brown and others (1970), Goerlitz and Brown (1972), and Fishman and Brown (1976).

Using prescribed techniques of sample preservation, water samples for the determinations of major inorganic chemical constituents, trace elements, and pesticides were analyzed by the U.S. Geological Survey National Water-Quality Laboratory--Atlanta, in Doraville, Ga. Water samples for the determinations of nitrogen, phosphorus, organic carbon, turbidity, and chemical oxygen demand were analyzed by the U.S. Geological Survey Water-Quality Service Unit, in Ocala, Fla. Water samples for the determinations of hydrogen sulfide, dissolved oxygen, bicarbonate, and pH were analyzed in the field at the time of collection.

GENERAL HYDROGEOLOGY OF THE STUDY AREA

The Floridan aquifer system, in the general area of the Collier Manor wastewater treatment plant, is a system of water-bearing strata, mostly permeable limestone, interspersed with semiconfining beds of dense carbonates or chalk and some clay (fig. 2). The aquifer system lies about 500 feet beneath the surface and extends to a depth of about 3,700 feet. Impermeable carbonate rock lies beneath the aquifer system and is about 700 feet thick (Miller, 1984).

Confining beds of relatively impermeable sands, clays, and marl about 300 feet thick are above the Floridan aquifer system. The Biscayne aquifer, from which Broward County draws its water supply, is above these confining beds. At Pompano Beach the top of the Biscayne aquifer is at land surface and extends to a depth of about 200 feet (Schroeder and others, 1958).

The head of the upper part of the Floridan aquifer system in the Pompano Beach area exceeds 40 feet above sea level (Healy, 1982). Land surface at the Collier Manor plant is about 22 feet above sea level. Thus, the artesian pressure is sufficiently high to cause wells that tap the aquifer system to flow freely at land surface. Contours of the head indicate that ground-water flow within the Floridan aquifer system is toward the Atlantic Ocean.

GENERAL WATER QUALITY OF THE STUDY AREA

Biscayne Aquifer

The Biscayne aquifer is the source of the public water supply for the population served by the Collier Manor wastewater treatment plant. The general chemical composition of water from the Biscayne aquifer in the vicinity of Collier Manor is given in table 1. The major ionic composition of the

water is calcium bicarbonate with a dissolved-solids concentration of about 300 mg/L (milligrams per liter). The data shown in table 1 represent a single sample of the Pompano Beach public water supply collected in 1976 (Irwin and Healy, 1978), and no doubt, slight seasonal variations occur. However, there is little indication that the major composition of water in the area varies significantly as Grantham and Sherwood (1968), Sherwood and others (1973), and Healy (1977) all report very similar quality for the Pompano Beach area.

Table 1.--General comparison of selected water-quality characteristics among the public-water supply for Pompano Beach (Biscayne aquifer), the native water in Floridan aquifer system in the wastewater injection zone, and the initial backflow from Collier Manor injection well 2

	Concentrations in milligrams per liter, except as noted		
	Biscayne aquifer ¹	Floridan aquifer system ²	Initial backflow ³
Calcium (Ca)	90	156	97
Magnesium (Mg)	2.4	166	4.7
Sodium (Na)	14	1,400	60
Potassium (K)	1.8	45	18
Bicarbonate (HCO ₃)	248	163	318
Sulfate (SO ₄)	39	512	2.4
Chloride (Cl)	21	2,360	84
Nitrate, as N	.43	.07	.01
Fluoride (F)	.2	1.2	.8
Dissolved solids, (sum of constituents)	293	4,720	450
Specific conductance (umho/cm at 25°C)	540	7,870	1,050
Hardness as CaCO ₃	240	1,070	260
Noncarbonate hardness as CaCO ₃	37	957	1
Color (Pt-Co units)	10	0	30
Iron (Fe)	.18	.24	1.1
Silica (SiO ₂)	8.2	15	14
Suspended solids (residue at 105°C)	--	--	48
Nitrogen, ammonia as N	--	--	38
Nitrogen, total Kjeldahl	--	--	39
Phosphorus, total as P	--	--	2.5
Carbon, total organic	--	--	20

¹Collected in 1975.

²Collected in 1959. (Considered to approximate the chemical composition of the native water in the injection zone.)

³Sample collected at 0.002 Mgal/d. (Considered to approximate the chemical composition of Collier Manor treatment plant effluent prior to injection.)

Floridan Aquifer System

The chemical composition of water from the Floridan aquifer system at the Collier Manor wastewater treatment plant, at an approximate depth of 1,000 to 1,150 feet, is shown in table 1. This sample was collected from the Collier Manor injection well 1 in 1959 prior to wastewater injection. This analysis indicates that the chemical composition of the native water in the Floridan aquifer system at this location and in the injection zone was predominantly sodium chloride with a dissolved-solids concentration of 4,720 mg/L.

Treatment Plant Effluent

Detailed chemical analyses were not performed on the effluent from the Collier Manor plant prior to injection. The lack of data on the chemical composition of original effluent placed a constraint on the interpretation of the study results and this data deficiency should be noted in following sections.

Because complete chemical analysis of the treatment plant effluent prior to injection was not available, the chemical composition of the first backflow sample (0.002 M/gal) was used as an approximation of the original effluent (table 1). This, of course, was somewhat conjectural in that the injected effluent likely underwent, at least minimally, some geochemical or biochemical transformation or attenuation during its residence in the subsurface. The plant was abandoned in January 1975, but the initial backflow samples were not collected until late March and April 1975. Therefore, the minimum subsurface residence time of the injected effluent before backflow was 3 to 4 months.

The most notable difference between the injected effluent and the backflowed effluent was that the backflowed effluent was devoid of dissolved oxygen; whereas, the effluent prior to injection had a dissolved oxygen concentration of about 5 mg/L (table 2). This transition between an aerobic and anaerobic system, of course, likely induced some chemical changes. However, gross changes in the major inorganic chemical composition of the effluent probably did not occur.

Table 2.--Summary of water-quality analyses of effluent from the Collier Manor wastewater treatment plant, October 1973 through October 1975

[Analytical data furnished courtesy of the Broward County Environmental Quality Control Board. Concentrations in milligrams per liter, except as noted]

	Samples	Mean	Range
Dissolved solids, (residue at 180°C)	21	313	142-656
Suspended solids, (residue at 105°C)	35	24	4-84
Turbidity (JTU)	32	12	2-38
Nitrogen, ammonia as N	33	15	0.2-33
Phosphorus, total as P	35	2.1	.04-5.4
Carbon, total organic	8	46	21-78
Biochemical oxygen demand	35	19	1-80
pH (units)	35	--	6.5-7.3
Dissolved oxygen	35	4.6	4.0-7.1

WATER QUALITY OF BACKFLOW

General Water Quality of Collier Manor Backflow

A summary of the chemical and physical analysis of backflow from Collier Manor injection well 2 is given in table 3. On the average, the backflow was predominantly calcium bicarbonate with a dissolved-solids concentration of about 560 mg/L. Concentrations of nitrogen (mainly ammonia), phosphorus, chemical oxygen demand, and hydrogen sulfide were notably elevated over those usually encountered in water from the Floridan aquifer system. Over the range of backflow (0.002-66.1 Mgal), the levels of most of the chemical and physical variables had considerable variability except calcium, hardness, and ammonia.

The overall quality of the backflowed effluent (table 3) was of somewhat poorer quality than that estimated for the original Collier Manor effluent prior to injection (tables 1 and 2), or secondary treated municipal effluent in general. Consequently, the backflowed effluent, as defined by this study, would generally require treatment before it would be suitable for most uses under existing State regulations.

Table 3.--Summary of chemical and physical analyses of backflowed effluent from injection well 2 for the periods March to August 1975 and April 1976 to March 1977

	No. of samples	Concentrations in milligrams per liter, except as noted		
		Mean	Median	Range
Calcium (Ca)	12	90	92	82-97
Magnesium (Mg)	12	7.6	6.7	4.7-13
Sodium (Na)	12	76	64	53-130
Potassium (K)	12	13	13	4.0-20
Bicarbonate (HCO ₃)	25	459	448	408-568
Sulfate (SO ₄)	15	37	38	11-63
Chloride (Cl)	21	104	84	74-240
Hardness (Ca, Mg)	11	257	260	200-240
Dissolved solids, (sum of constituents)	12	562	526	450-761
Specific conductance (umho/cm at 25°C)	15	1,040	1,040	600-1,320
Phosphorus, total as P	36	1.8	1.7	.24-3.5
Nitrogen, ammonia as N	40	32	32	31-34
Nitrogen, total Kjeldahl as N	40	35	35	26-42
Carbon, total organic	38	11	10	5.0-42
Chemical oxygen demand (high level)	32	57	60	20-88
Hydrogen sulfide (H ₂ S)	25	32	32	17-53
pH (units)	24	--	6.9	6.1-7.1
Suspended solids, (residue at 105°C)	20	10	5	1-48
Turbidity (JTU)	35	77	75	15-160

Major Inorganic Composition and Cumulative Volume of Backflow

The major inorganic composition of backflow samples collected periodically from March 1975 through February 1977 is shown in milliequivalents per liter (meq/L) in figure 4. (Note: Concentration of ammonia contributes significantly to the cation meq/L.) The figure shows that the backflow underwent both an increase in mineralization and a distinct change in the ionic composition as a function of cumulative backflow. This increase in mineralization and transition in ionic composition of the backflow suggests a simple mixing (blending) of the injected effluent and the native water in the zone of injection. The mixing aspect is treated more quantitatively in following sections. For general reference, the ionic composition of the native water prior to injection (table 1) is also illustrated in figure 4.

The dissolved-solids concentration of the backflow ranged from about 450 to 520 mg/L (± 20 meq/L) for about the first 10 Mgal of cumulative backflow, and progressively increased in concentration to a maximum of 761 mg/L (28 meq/L) at a cumulative volume of 66.1 Mgal. Increases in some individual ions such as sodium and chloride were notable, while calcium and bicarbonate did not increase significantly.

In addition to a general increase in salinity, the basic ionic composition of the backflow also changed as a function of cumulative volume. For example, the milliequivalents of sodium ranged from about 23 to 30 percent of the total cation milliequivalents per liter in samples taken when cumulative backflow was 10 Mgal or less, but increased to 38 to 43 percent when cumulative backflow was between 40 to 66.1 Mgal. Similarly, chloride milliequivalents ranged from about 21 to 30 percent during initial backflow, but increased to 46 percent of the total anion milliequivalents per liter at 66.1 Mgal.

Concentration of Chloride as a Function of Cumulative Volume of Backflow

The concentrations of chloride was a function of cumulative volume of backflowed effluent (fig. 5). A regression analysis indicated that the relation was statistically significant at the 99 percent probability level, with an explained variance (r^2) of 0.99.

The linear increase in the concentrations of chloride as a function of backflow likely reflect simple mixing of the injected effluent and the moderately-saline native water in the injection zone. (Note: Backflow was plotted on a logarithmic scale for graphical convenience in fig. 5; thus, the linear function indicates curvature.)

This change in the concentration of chloride was used to estimate the mixing ratio. Chloride was used because it is a conservative ion which is usually retained in solution during most of the processes which often attenuate other ions (Hem, 1970, p. 172). It is noted, however, that the effluent chemistry was somewhat variable in composition; therefore, the following mixture percentages should be considered only as approximations.

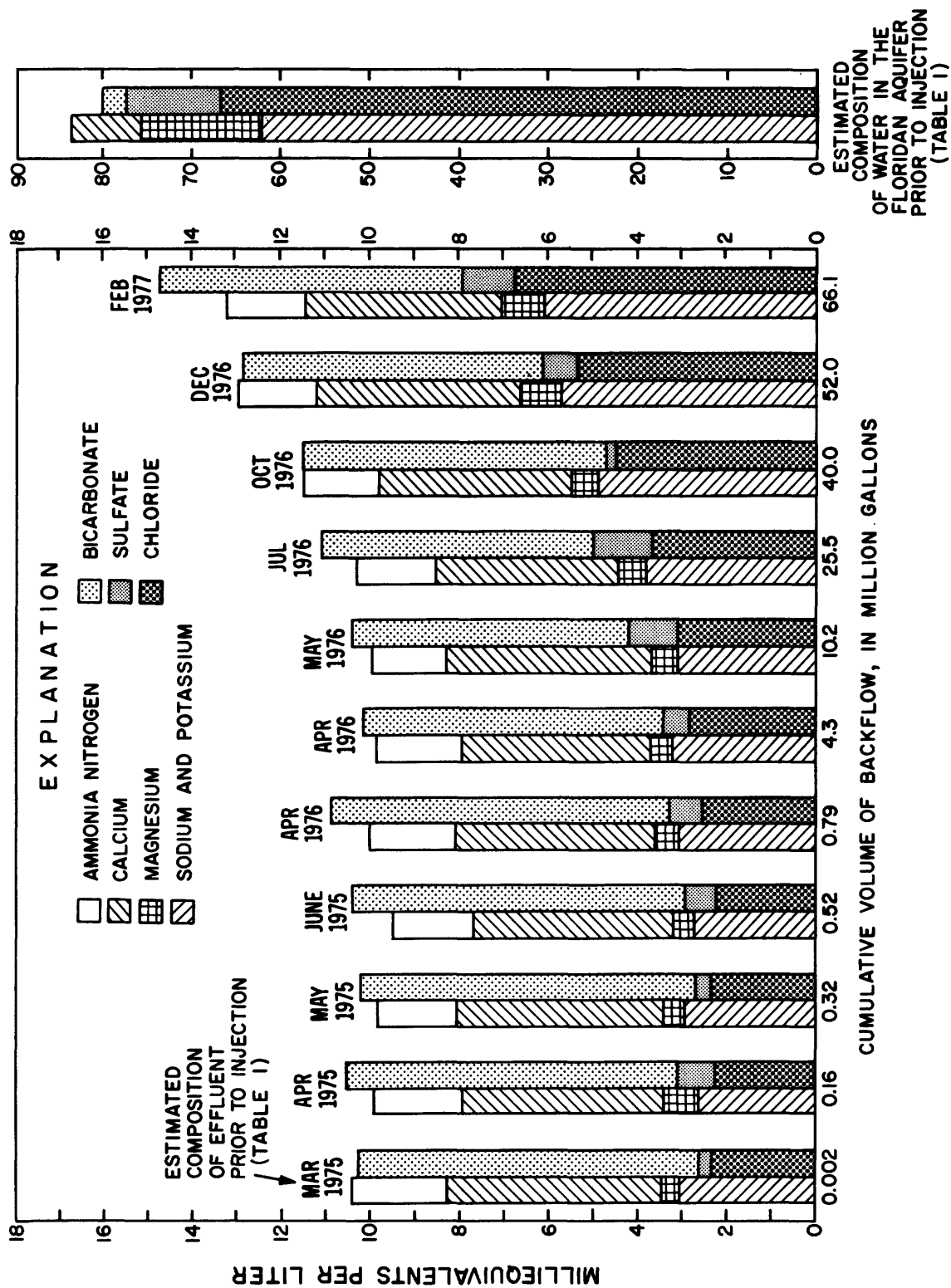


Figure 4.--Ionic composition of backflow samples collected at various cumulative volumes of backflow and the native water in the Floridan aquifer system.

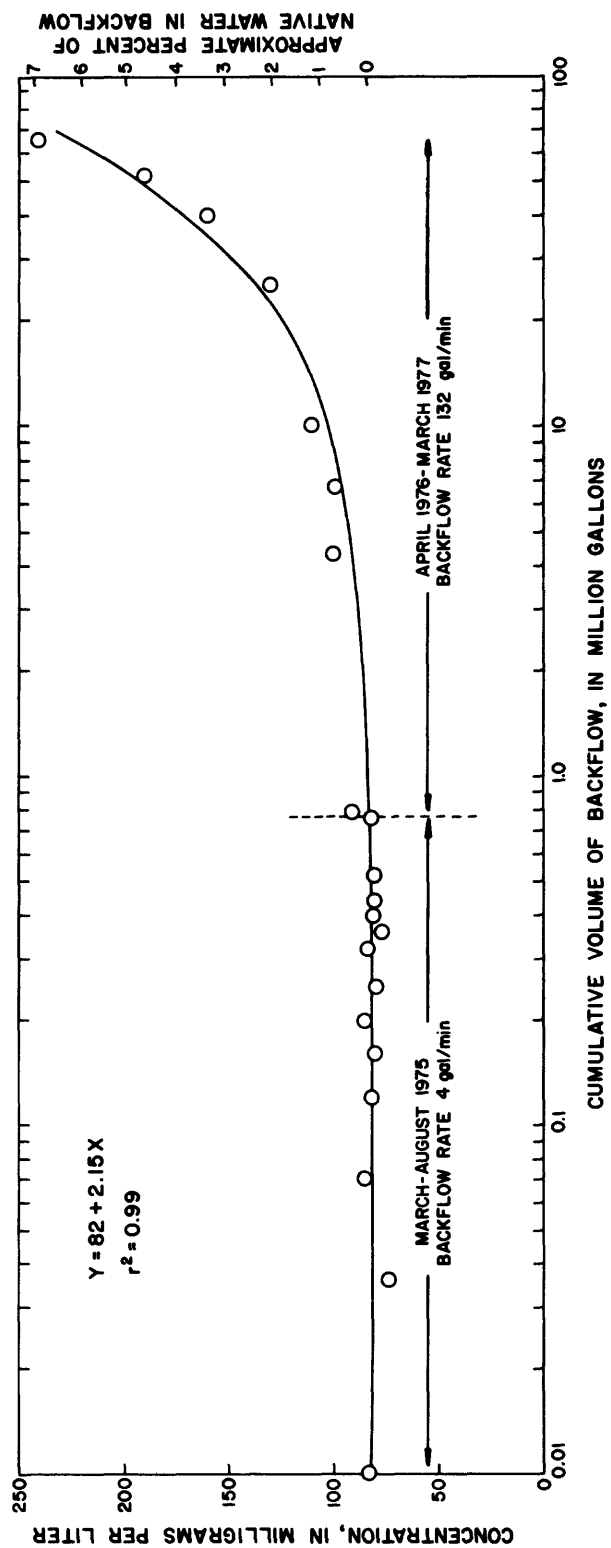


Figure 5.--Concentration of chloride in backflow samples in relation to the cumulative volume of backflow.

The mixture percentages shown in figure 5 were computed using the following equation:

$$C_1 V_1 + C_2 V_2 = C_3 (V_1 + V_2) \quad (1)$$

where

- C_1 = concentration of chloride in the original effluent in milligrams per liter (estimated at 84 mg/L from table 1),
- V_1 = percent volume of initial backflowed effluent,
- C_2 = concentration of chloride in the native water in the injection zone in milligrams per liter (estimated at 2,360 mg/L from table 1),
- V_2 = percent volume of native water,
- C_3 = concentration of chloride in mixture of native water and initial backflowed effluent.

For example, substituting appropriate values to estimate a mixture of 7 percent native water and 93 percent effluent:

$$84 \text{ mg/L} \times 0.93 + 2,360 \text{ mg/L} \times 0.07 = 243 \text{ mg/L} \quad (1)$$

Thus, a mixture of 7 percent native water (C_2) and 93 percent original effluent (C_1) would have an estimated chloride concentration of about 243 mg/L. The concentration of chloride at a cumulative volume of 66.1 Mgal was 240 mg/L (fig. 5); therefore, it is reasonable to assume, stoichiometrically, that the backflow contained about 6 to 7 percent native water.

The increase in the concentration of dissolved solids generally corroborates the mixing estimate of 7 percent. That is, a mixture of 93 percent original effluent having a dissolved solids concentration of 450 mg/L (table 1) and 7 percent native water having a dissolved solids concentration of 4,720 mg/L (table 1) would have a concentration of 749 mg/L. The concentration of dissolved solids in the final backflow sample (66.1 Mgal) was 761 mg/L.

The regression line (fig. 5) developed by the regression analysis of all the chloride observations as a function of cumulative volume would give a slightly different final mixing percentage. The concentration of chloride at a cumulative volume of 66.1 Mgal from the regression line is about 224 mg/L, rather than 240 mg/L actually determined in the sample. In terms of estimating the relative mixing percentage, however, the difference is minor. For instance, the native contribution would be estimated at 6.2 percent at 66.1 Mgal if a concentration of 224 mg/L is assumed a better estimate (because it is the mean based on all the empirical data) than an estimate from the single sample (240 mg/L). The estimate of 6.2 percent native water was determined using the following equation modified from Hem, 1970, p. 270-275:

$$XC_1 + (1-X) C_2 = C_3 \quad (2)$$

substituting

$$\begin{aligned} 84X + (1-X) 2,360 &= 224 \\ X &= 93.8\% \text{ (original effluent)} \\ 1-X &= 6.2\% \text{ (native water)} \end{aligned}$$

Nevertheless, the contribution of native water in the final backflow sample collected at a cumulative volume of 66.1 Mgal likely was 6 to 7 percent, using either the final sample (240 mg/L) or the regression line (231 mg/L) to compute the estimate.

Kjeldahl Nitrogen, Total Phosphorus, and Hydrogen Sulfide
as a Function of Cumulative Backflow

The relations between the concentrations of three nonconservative variables as a function of backflow are shown in figures 6 to 8. These variables were selected because they were quite abundant in the injected effluent and because they are usually nonconservative in most subsurface environments. That is, their concentrations are usually controlled by many processes other than simple mixing with native water. The initial backflow samples were not as representative of the nonconservative variables of the original effluent as they were for the major inorganic variables because the original effluent prior to injection was aerobic, but the backflow during the sampling was anaerobic. The anaerobic environment probably did not affect the relative concentrations of such inorganic variables as chloride. However, this change, for example, did result in a much higher concentration of hydrogen sulfide in the anaerobic backflow than in the aerobic effluent prior to injection. The concentrations of the other nonconservative variables in the original effluent were no doubt also altered in the anaerobic injection zone to some extent by such processes as ammonification of organic nitrogen and solubilization of organic phosphorus. Thus, the relations portray only a limited perspective of trends.

The relations were assessed by regression analysis. A linear and several curvilinear regression models were used to describe the concentration trends as a function of cumulative backflow. Statistically, the data were generally best described by a logarithmic curve in the form ($y = a + b \ln x$). However, the variances explained by the regression (r^2) were all less than 50 percent.

Mindful of the fallibility of the relation, Kjeldahl nitrogen was used to assess whether its decrease in relation to cumulative backflow could be attributed solely to dilution resulting from simple mixing of the injected effluent with the water in the Floridan aquifer system. Because no data were available on the concentration of Kjeldahl nitrogen in the native water, the mixture percentages were estimated using the following equation:

$$XC_1 + (1-X) C_2 = C_3 \quad (2)$$

where

C_1 = the Kjeldahl nitrogen concentration in the original effluent (estimated at 39 mg/L from table 1),

C_2 = The Kjeldahl nitrogen concentration in the native water (estimated at 0, 1, and 5 mg/L to bracket a reasonable range in concentrations because no data were available),

C_3 = The Kjeldahl nitrogen concentration in the mixture of the original effluent and the native water (estimated at 32 mg/L based on an average of 12 samples of backflow from a cumulative volume of 30 to 66 Mgal from fig. 6),

X = the percent volume of C_1 in C_3 ,

1-X = the percent volume of C_2 in C_3 .

Solving the equation using the estimated concentrations of Kjeldahl nitrogen of 0, 1, and 5 mg/L for C_2 (native water) resulted in C_1 mixture percents (X), respectively, of 82, 82, and 79 and C_2 mixture percents (1-X) of 18, 18, and 21, as compared with about 93 and 7 percent based on chloride concentration.

Thus, estimating a native concentration of Kjeldahl nitrogen in a range of 0 to 5 mg/L, the previous exercise suggests that the final backflow mixture would need to have been about 20 percent native water. The ± 20 percent mixture of native water needed to balance the overall nitrogen decrease suggests that other processes, in addition to dilution by native water, partially controlled the decrease of Kjeldahl nitrogen from an estimated ± 39 to ± 32 mg/L. As most of the Kjeldahl nitrogen was as ammonia, it is plausible that the decreases were, in part, because of microbial activity and adsorption or ion exchange within the aquifer system substrate.

Using the same approach to account for the decrease in total phosphorus, it was estimated that an even greater percentage of native water was required to balance the mixture. The total phosphorus estimates were made using an original effluent concentration (C_1) of 2.5 mg/L (table 1), a final backflow concentration (C_3) of 1.3 mg/L based on an average of 10 samples of backflow from 33 to 66 Mgal (fig. 7), and an estimated native-water concentration (C_2) of 0 to 0.1 and 1 mg/L to bracket a reasonable range because no data were available. Using these concentrations, the final backflow mixtures would need to have been about 52 to 20 percent effluent and 48 to 80 percent native water, rather than 93 and 7 percent estimated from chloride concentrations.

A mixing of at least 50 percent effluent and 50 percent native water would have been required to account for a final phosphorus concentration of about 1.3 mg/L. Therefore, it is likely that much of the observed decrease was because of precipitation of ionic complexes or compounds of phosphorus of low solubility with such metals as calcium, aluminium, and iron. Also, some ionic forms of phosphorus will adsorb to metal oxides, especially ferric hydroxide (Hem, 1970, p. 185) which also would serve to reduce concentrations.

Hydrogen sulfide (fig. 8) decreased about 30 percent from an average concentration of 37 mg/L for the backflow range of 0 to 0.8 Mgal to 26 mg/L for the backflow range of 30 to 66 Mgal. While dilution with the native water was probably a partial factor in this reduction, mixing likely would not account for the approximate 30 percent decrease. Some of the reduction may have been because of precipitation as ferrous sulfide (FeS) which was continually observed in the form of particulate iron scale in the backflow. In addition to iron, other metals perhaps contributed to hydrogen sulfide losses through precipitation; as Hem (1970, p. 170) reports, the sulfides of most metals are low in solubility and sulfides often seem to be lost from solution in ground water, probably by precipitation of sulfides, before the water has moved any great distance.

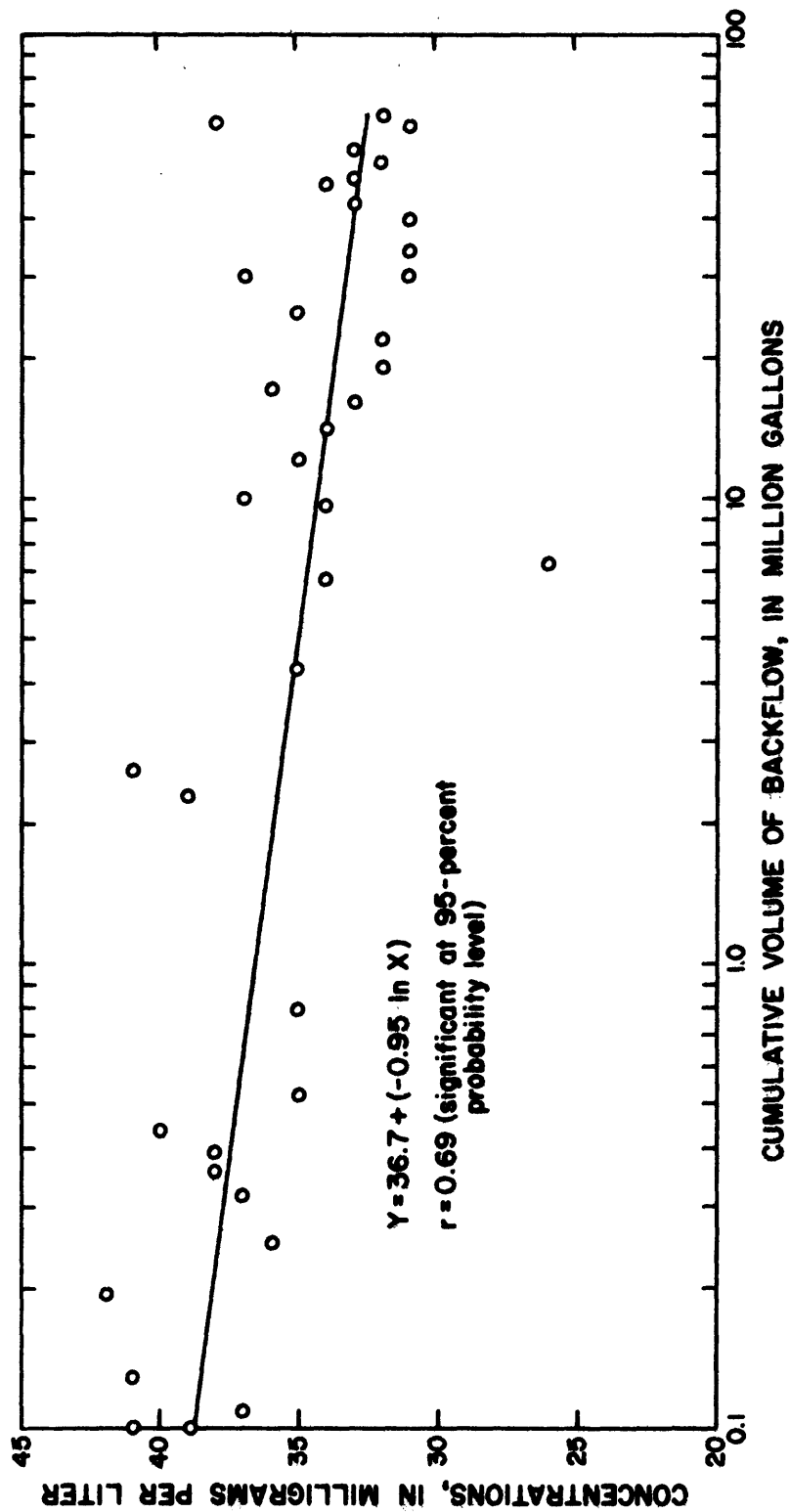


Figure 6.--Concentration of total Kjeldahl nitrogen in backflow samples in relation to the cumulative volume of backflow.

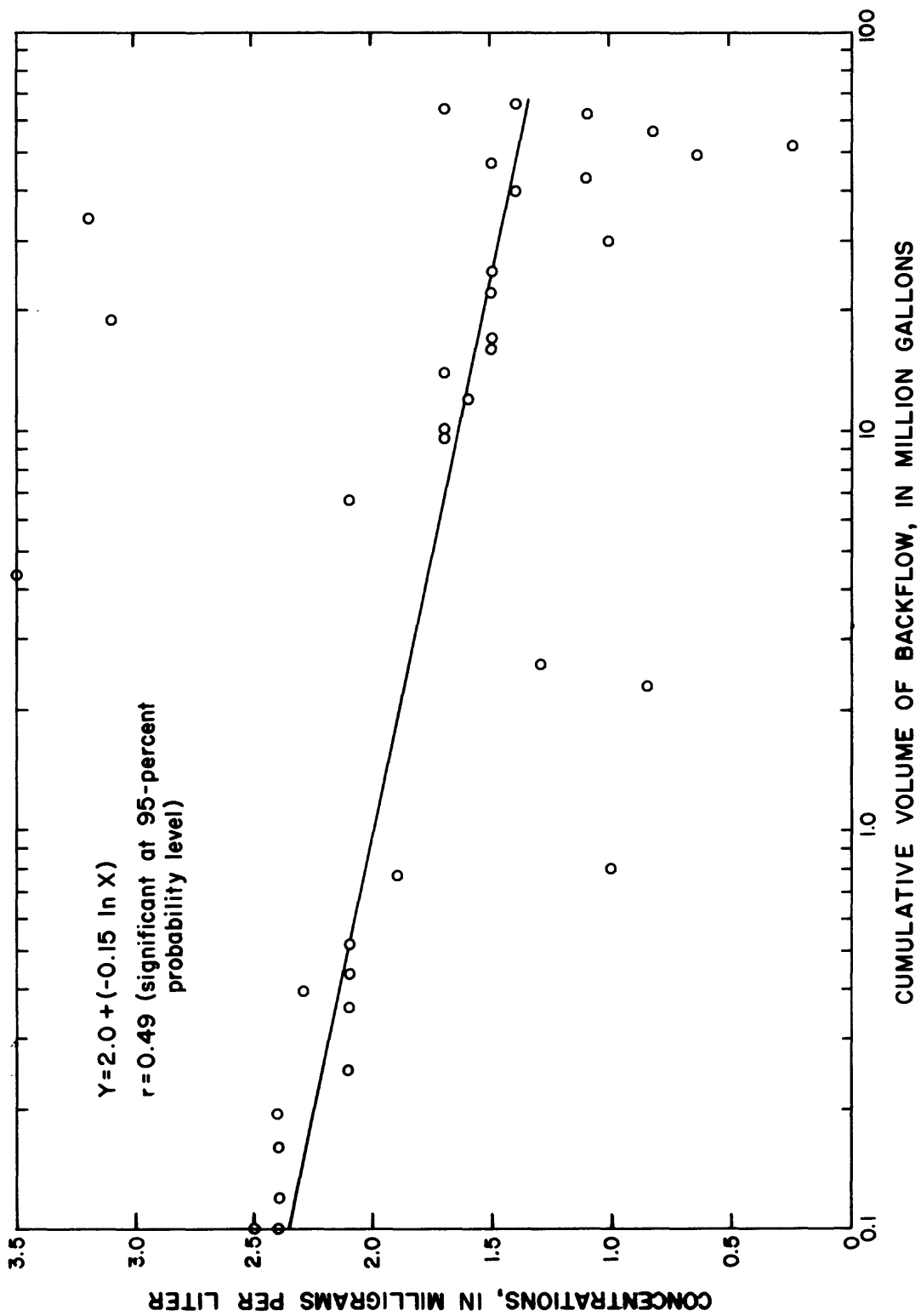


Figure 7.--Concentration of total phosphorus in backflow samples in relation to the volume of cumulative backflow.

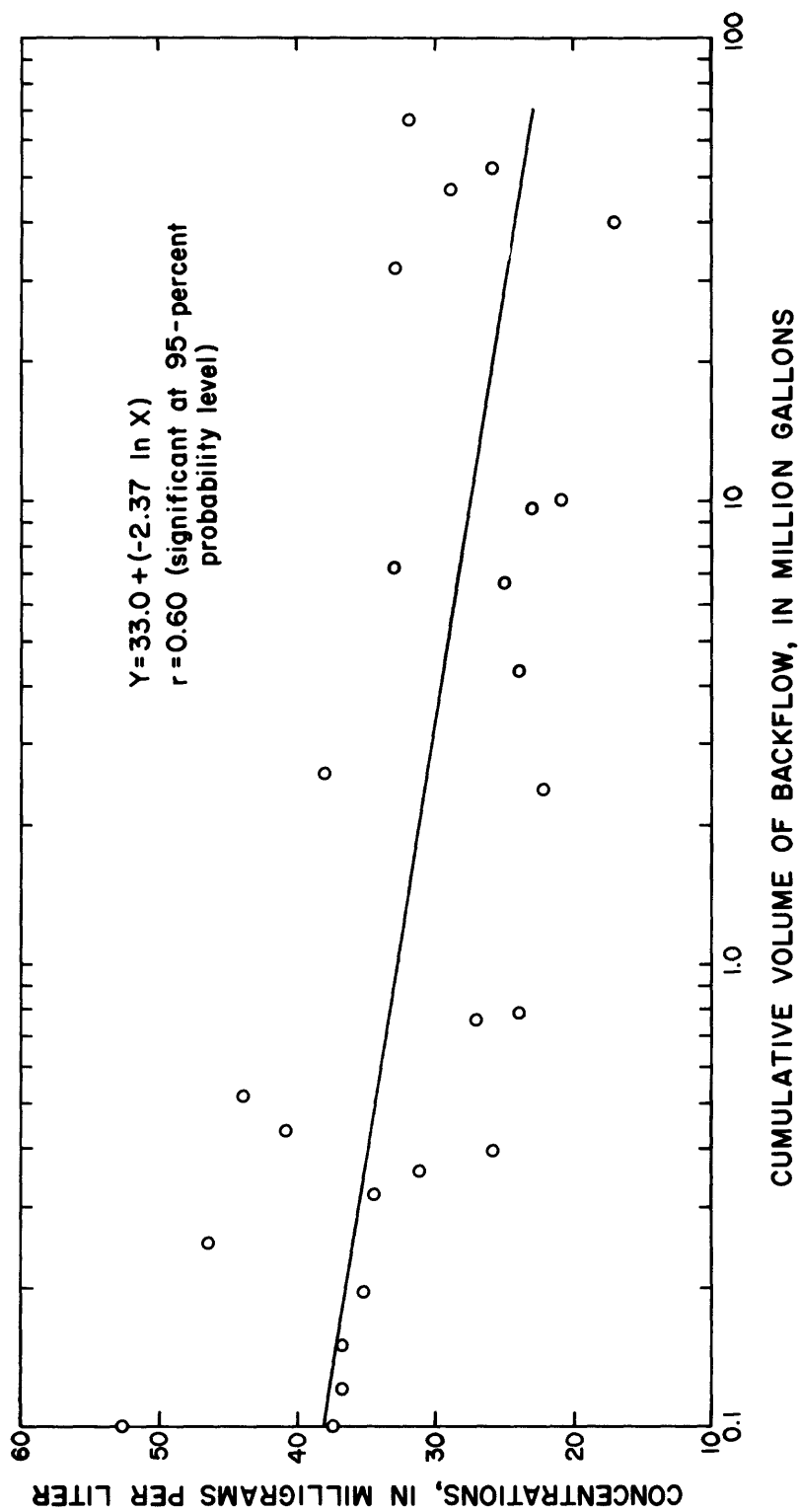


Figure 8.--Concentration of hydrogen sulfide in backflow samples in relation to the volume of cumulative backflow.

Selected Minor Elements and Pesticide Compounds

Minor Elements

Backflow from injection well 2 was sampled periodically for selected minor (trace) elements and a summary of the analytical results of this sampling is presented in table 4. Elevated concentrations of total iron were the most notable of the analyses with 5 of the 12 samples having total iron concentrations in the milligram range. The average concentration of total iron in the backflow was about 3,000 ug/L (micrograms per liter) though there was considerable variation and little evidence of decrease. The origin of the high concentrations likely resulted from the dislodging of the iron scale from the well casing during backflow. Iron scale is common in wells located in organically rich, anaerobic systems where bacteria reduce sulfate to hydrogen sulfide (H_2S) while elemental iron is autocatalytically reduced to ferrous iron (Fe^{2+}). The reduced iron reacts with hydrogen sulfide and water to yield ferrous sulfide (FeS), a common iron-scale precipitate.

Total concentrations of manganese, copper, lead, nickel, and zinc were consistently detected throughout the backflow sampling at levels of analytical confidence, but no particular trend was evident, except for perhaps barium and nickel. The other trace elements monitored were generally below analytical detection.

Pesticide Compounds

At a sampling frequency similar to the trace elements, backflow samples were collected for selected pesticide compounds of the organochlorine and phosphorothioate insecticide and chlorophenoxy herbicide groups. The herbicide, silvex, was detected in two backflow samples (0.002 and 0.793 Mgal) at concentrations of 0.05 ug/L; other pesticides were not detected in the backflowed effluent.

SUMMARY AND CONCLUSIONS

The quality of a secondary treated effluent backflowed from a wastewater injection well was sampled from March 1975 through March 1977. The sampling site was located at the Collier Manor wastewater treatment plant in Broward County, Fla. From about 1959 through January 1975, this plant had injected (through a 2-well system) approximately 3.5 billion gallons of secondary treated effluent (domestic and stormwater sewage) at a rate of about 0.6 Mgal/d into a moderately saline zone (1,000-1,250 feet deep) of the Floridan aquifer system.

The purpose of the reconnaissance was to measure and describe the levels of selected water-quality variables in the backflowed effluent throughout the 69.2 Mgal backflow period. The results of this study will provide some general background on the efficacy of recovery of injected effluent.

The sampling was conducted during two backflow periods and two rates of backflow. From March to August 1975, injection well 2 was backflowed at an average rate of about 4 gal/min for a cumulative volume of about 0.8 Mgal and 13 water samples were collected; from April 1976 to March 1977, the backflow was increased to an average rate of about 132 gal/min for a cumulative volume of about 69.2 Mgal and 27 samples were collected.

Table 4.--Summary of chemical analyses of trace elements in backflow from injection well 2 for the periods March to August 1975 and April 1976 to March 1977

[Total concentrations, in micrograms per liter]

Date of collection	Cumulative volume of backflow in gallons	Arsenic (As)	Barium (Ba)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Silver (Ag)	Zinc (Zn)
03/23/75	0.002	1	600	1	13	110	18,000	14	300	<0.1	38	<1	1	30
04/22/75	.156	1	200	<1	10	12	260	<1	40	.6	26	<1	<1	60
05/20/75	.316	1	100	<1	10	32	1,800	14	60	.2	18	<1	<1	90
06/24/75	.517	<1	<100	<1	<10	9	320	2	40	.7	17	<1	<1	30
08/06/75	.763	<1	<100	<1	<10	28	750	11	50	.3	20	<1	<1	50
04/01/76	.793	1	<100	<1	10	30	920	7	250	<.1	12	<1	<1	30
04/27/76	4.3	1	<100	<1	<10	6	1,000	18	60	.2	17	<1	<1	40
05/21/76	10.2	<1	100	1	<10	32	1,200	10	10	<.1	13	<1	<1	60
07/26/76	25.5	<1	<100	2	--	8	310	38	10	.2	20	<1	<1	50
10/05/76	40.0	1	100	1	10	2	710	2	110	.1	13	<1	<1	40
12/06/76	52.0	1	<100	1	--	16	11,000	48	--	.1	9	<1	<1	--
02/14/77	66.1	1	<100	<1	10	120	--	21	120	.1	16	<1	<1	100

The general findings of the reconnaissance sampling are as follows:

1. The major inorganic composition of the backflowed effluent increased in dissolved solids and changed in ionic composition during the 69.2 Mgal backflow reconnaissance primarily because of mixing with the native water in the injection zone. A mixing (dilution) model was developed for chloride concentrations that indicated that the composition of backflow at a cumulative volume of about 66 Mgal was a mixture of 6 to 7 percent native water and about 93 percent injected effluent.
2. The dissolved-solids concentrations of the backflowed effluent ranged from about 450 to 520 mg/L for about the first 10 Mgal of backflow, but progressively increased to a maximum of 761 mg/L at a cumulative volume of 66.1 Mgal. The increase from 450 mg/L in the initial backflow to 761 mg/L in backflow at 66.1 Mgal substantiates a 6 to 7 percent contribution of native water.
3. Selected nonconservative variables, Kjeldahl nitrogen, phosphorus, and hydrogen sulfide, were also monitored as a function of backflow. Unlike the direct relation of the conservative inorganic variables, the nonconservative variables indicated an inverse relation with backflow. None of these relations, however, had an explained variance (r^2) above about 50 percent.
4. Some of the decreases in the concentrations of nitrogen, phosphorus, and hydrogen sulfide during backflow were greater than could be attributed to a 6 to 7 percent mixture with the native water. Microbial activity, ion exchange, precipitation, and sorption likely contributed to concentration attenuation.
5. Of the trace elements monitored, high concentrations of iron were the most notable and were likely caused by the dislodging of ferrous sulfide deposits in the injection well and immediate aquifer. Ferrous sulfide formation was probably the result of microbial processes induced by the organically enriched, reducing aquatic environment in the injection zone.
6. Using a chloride concentration of 250 mg/L in the backflow as a maximum limit, only about 2 percent of the 3.5 billion gallons of injected effluent was recovered.
7. Overall, the backflowed effluent was of poor quality and would have needed treatment before it met standards acceptable for most uses under present State regulations.

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